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SPATIAL VARIABILITY OF FLOODPLAIN SEDIMENTATION AT THE EVENT SCALE IN THE RHINE–MEUSE DELTA, THE NETHERLANDS

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ABSTRACT

This article addresses spatial variability of comtemporary floodplain sedimentation at the event scale. Measurements of overbank deposition were carried out using sediment traps on 11 floodplain sections along the rivers Waal and Meuse in The Netherlands during the high-magnitude flood of December 1993. During the flood, sand sheets were locally deposited behind a natural levee. At distances greater than 50 to 100 m from the river channel the deposits consisted mainly of silt- and clay-sized material. Observed patterns of deposition were related to floodplain topography and sediment transporting mechanisms. Though at several sites patterns were observed that suggest transport by turbulent diffusion, convection seems the dominant transporting mechanism, in particular in sections that are bordered by minor embankments. The average deposition of overbank fines ranged between 1·2 and 4·0 kg m^{-2} along the river Waal, and between 1·0 and 2·0 kg m^{-2} along the river Meuse. The estimated total accumulation of overbank fines (not including sand sheets) on the entire river Waal floodplain was 0·24 Mton, which is 19 per cent ot the total suspended sediment load transported through the river Waal during the flood. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: floodplains; sedimentation; spatial variability; floodplain morphology.

INTRODUCTION

Overbank deposition may be an important term in the sediment budget of a river basin. A prolonged floodplain sedimentation reduces the transporting capacity of the high-water bed, and, with the sediment, pollutants are brought into the floodplain soils. The awareness of the role of fine suspended sediment in fluvial systems has led to an increased interest in (contemporary) floodplain sedimentation rates.

When overbank flow occurs, sediment can be transferred from the main channel to the floodplain by different mechanisms. Coarse sediment may be transported by traction as bed load and will be deposited close to the channel. Fine-grained sediment is usually transported in suspension and is deposited further away from the channel. Differences in flow velocity and suspended sediment concentrations between the main channel and the adjacent floodplain may result in a lateral diffusive transfer of suspended sediment at the interface between the channel and the floodplain (Allen, 1985; Pizzuto, 1987). In most situations, however, a flow component perpendicular to the channel is present, resulting in sediment transfer mainly by convection (James, 1985; Pizzuto, 1987; Marriott, 1992). The amount of sediment conveyed into the floodplain area depends on the sediment concentration in the river. Suspended sediment concentrations can vary in space and time. During a flood, hysteresis effects often occur in the relation between river discharge and sediment concentration. Patterns in sediment accumulation depend on floodplain topography, including local embankments (‘minor dykes’) that protect a floodplain from inundation during low-magnitude floods. Minor river dykes also determine inundation times, flow patterns, and the transfer of sediment onto the floodplain.

A proper understanding of the role of all these factors and mechanisms that control floodplain sedimentation demands in the first place a great number of measurements of sediment deposition. Moreover, data on floodplain sedimentation with a high degree of spatial and temporal resolution are needed to test models of floodplain sedimentation (Pizzuto, 1987; James, 1985; Marriott 1992; Mackay and Bridge, 1995).

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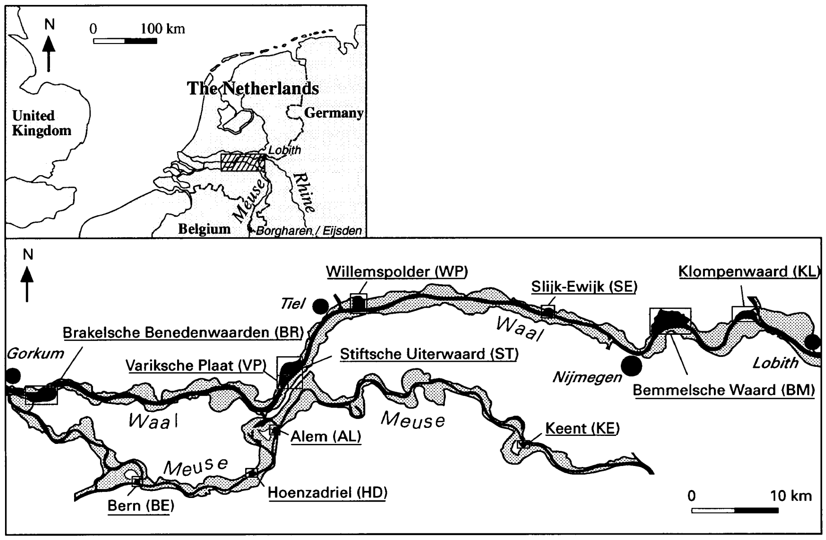

Figure 1. Location of the investigated floodplain sections

Various methods have been applied to determine rates and patterns of contemporary floodplain sedimentation. From measurements of conveyance losses, average sediment accumulation along a river stretch can be estimated (e.g. Lambert and Walling, 1987; Gretener and Strömquist, 1987; Walling *et al.*, 1986; Walling and Bradley, 1989). An indication of local variability in sediment accumulation may be obtained by reconnaissance surveys, carried out following a single flood event (Kesel *et al.*, 1974; Miller and Shoemaker, 1986; Brown, 1987). However, this method can only be used if sedimentation rates are sufficiently large. Sediment traps placed on the floodplain surface in advance of a flood event are used to document patterns of sediment accumulation, even when the amounts of sediment deposited are low (e.g. Mansikkaniemi, 1985; Lambert and Walling, 1987; Walling and Bradley, 1989; Gretener and Strömquist, 1987; Walling *et al.*, 1992; Nicholas and Walling, 1993). In these studies, however, detailed analyses of two-dimensional patterns of sediment accumulation were only carried out for very small floodplain areas. In addition, most studies were concerned with a single flood event. The results of these studies therefore do not allow comparison of sediment accumulation in floodplain sections with different topography, or during different flood events. As a consequence, little information is available on the effects of floodplain topography and flood characteristics on the amounts and patterns of sediment accumulation.

In a previous study by the authors, it was demonstrated that the spatial pattern of sediment deposition during a flood event can be well determined by using sediment traps made of artificial grass (Asselman and Middelkoop, 1995). This previous study, however, was carried out only in two small floodplain sections, and during a minor flood. In the present study patterns of floodplain sedimentation resulting from the high-magnitude flood of December 1993 were studied for a much larger floodplain area with varying topography. By comparing the results of sediment trap measurements from different sections, the observed patterns of sediment accumulation were related to floodplain topography, inundation times and possible sediment-transporting mechanisms. In addition, an estimate was made of the total amount of sediment deposited during the December 1993 flood on the entire river Waal floodplain.

STUDY AREA

The study was carried out in seven floodplain sections along the river Waal, and four located along the river Meuse (Figure 1). The river Waal is the largest distributary of the lower river Rhine in The Netherlands. The average Rhine discharge near Lobith (Dutch–German border) is about 2200 $m^3 s^{-1}$, of which the Waal transports two-thirds. Peak discharges usually range between 5000 and 10 000 $m^3 s^{-1}$. Near Lobith, the average suspended

Table I. Characteristics of the investigated floodplain sections

	Km no.	Area (ha)	Bank	Q_c ($m^2\ s^{-1}$)	n – avg. (days a^{-1})	n – 1993 (days)
Waal sections						
KL	869	113·0	L	5300	8·1	23
BM	880	420·0	D	6450	3·2	15
SE	893	9·2	L	5720	7·0	20
WP	911	22·0	D	7110	2·2	12
ST	921	150·0	D	6770	2·6	15
VP	922	30·0	L	5860	5·4	21
BR	948	180·0	L/D	8500	1–2	8
Meuse sections						
KE	178	16·1	L	1350	3·7	8
AL	210	9·0	X	1500	2·2	8
HD	215	15·0	X	1900	<1	4
BE	227	18·1	L	1600	1·4	8

Km no.=kilometre number in downstream direction along the river; Bank, L=natural levee; D=minor dyke; X=no natural levee or minor dyke; Q_c=critical discharge for sediment transport to floodplain; n – avg=average annual period of sediment influx; n – 1993=number of days of sediment influx during flood of December 1993–January 1994

sediment concentration is about 30 mg l^{-1}. During periods of high discharge, maximum concentrations vary between 120 and 200 mg l^{-1}. The average discharge of the river Meuse at the Eysden gauging station (Dutch–Belgian border) is 250 $m^3\ s^{-1}$; discharge peaks can be up to 2500 $m^3\ s^{-1}$. Average suspended sediment concentrations are about 30 mg l^{-1}; during high discharge periods maximum concentrations are between 150 and about 300 mg l^{-1}. The suspended load in both rivers consists mainly of clay, silt and fine sand (Rijkswaterstaat, 1992).

The most important characteristics of the studied floodplain sections are summarized in Table I. The size of the sampled floodplain sections ranges between 9 ha and 420 ha. The floodplain sections BM, WP and ST are protected from minor floods by small embankments (‘minor dykes’), which are 1 to 2·5 m high. The floodplain sections AL and HD have artificial banks, sloping gently upward from the river channel. The other sections are separated from the river channel by a small 0·2 to 1 m high natural levee. The sections KL, VP, BR and parts of the floodplain sections SE and ST still have their natural topography of scroll bars and depressions from fossil channels. The sections BM and WP have been levelled. The investigated Meuse floodplain sections show few differences in local elevation. Depending on the presence of minor dykes and differences in elevation, the average number of days per year that the floodplains are inundated and sediment is conveyed into the floodplain ranges from 1 day per year for sections BR and HD to 9 days per year and longer for the lower parts of VP. The investigated areas are mainly used as pasture land, with local tree stands and a few fields of arable land.

THE FLOOD OF DECEMBER 1993

After prolonged and heavy rainfall in western Europe during the week before Christmas 1993, major discharge peaks occurred in the rivers Rhine and Meuse. The recurrence time of the Rhine flood was about 40 years. The flood of the river Meuse was even more exceptional, since a flood of this magnitude had not occurred earlier in this century. The records of daily discharges and suspended sediment concentrations of both rivers during this period are shown in Figure 2. The grey/black bars below these graphs indicate the inundation periods of the floodplain sections. Inundation times varied between 5 days and more than 1 month.

SAMPLING CONFIGURATION AND LABORATORY ANALYSES

Sediment traps made of artificial grass with 1·5 cm long plastic blades, fixed to a pliable (plastic) base, were used to collect sediment deposited during overbank flooding. The artificial grass was assumed to approach the hydraulic roughness of the floodplain surface. The traps measured 50 cm×50 cm and were fixed to the floodplain surface with 10 cm long steel pins. One or two days before inundation, the traps were placed on the floodplains. Depending on the size of the floodplain section and the desired sample density, the number of

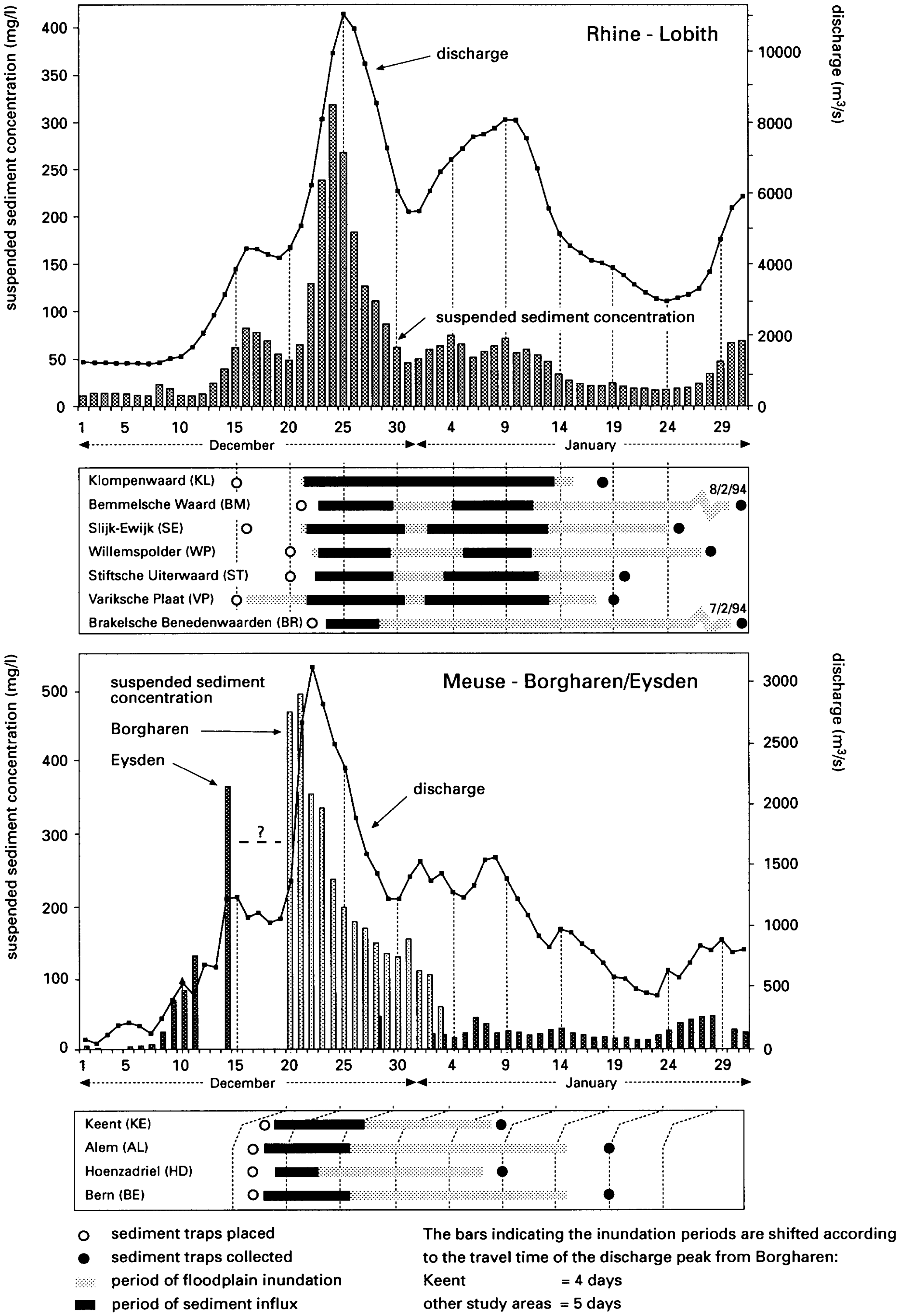

Figure 2. Discharge and suspended sediment concentration of the rivers Rhine and Meuse, and inundation periods of the investigated floodplain sections, December 1993–January 1994

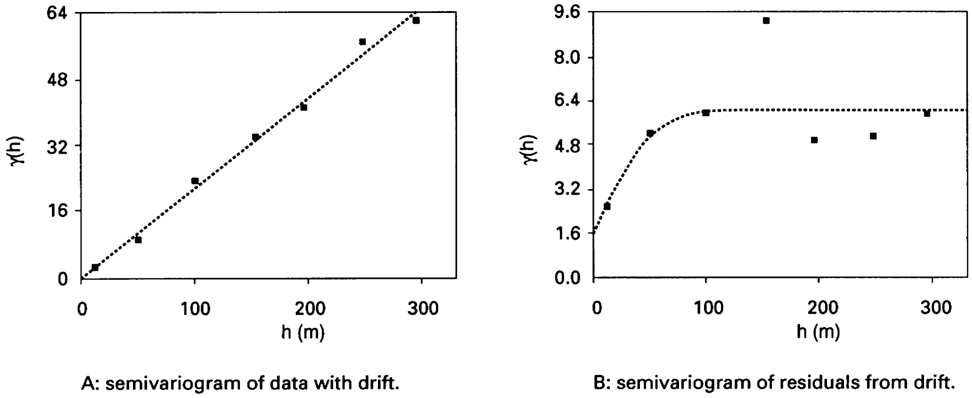

Figure 3. Variograms of the sediment trap measurements in the KL section

sediment traps varied between 24 and 96 per floodplain section. A relatively high sample density was applied in the sections KL, VP, KE and BE; relatively few traps were used in the floodplains BM, WP, ST and BR. The traps were placed in a semi-regular grid, consisting of several transects that were oriented in the direction perpendicular to the main stream. Close to the river channel the sampling interval along the transects was 5 m, increasing to about 100 m at distances of more than 150 m from the main stream. The spacing between the transects varied from 100 m at densely sampled areas to about 250 m in the large floodplain sections. To determine differences in sediment accumulation over short distances, several traps were placed in clusters. The number of traps within one cluster varied from three to ten; their spacing ranged from 1 to 5 m.

As soon as the flood had receded, the traps were taken to the laboratory for analysis of the sediment. A few traps that were placed on natural levees were not found because they were either washed away as a result of high current velocities or wave action, or they were buried by a sheet of sand more than 10 cm thick. In the laboratory, the sediment was removed from the traps using a high-pressure cleaner, and was collected in a bucket. The sediment settled out after addition of 30 per cent HC1 solution; subsequently, the water was siphoned off and the sediment was dried and weighed. For all samples from Keent and the Variksche Plaat and for samples from transects in the other floodplains the sand content was determined. For some samples the clay percentage and the organic matter content were also determined.

STATISTICAL INTERPOLATION METHODS

To calculate the total amount of deposited sediment for each test area, and to determine the spatial variability of the sediment deposition, the sets of sediment trap measurements were interpolated using kriging. Kriging is a form of weighted local averaging. It is an optimal interpolation method in the sense that the interpolated values are unbiased, and have a minimum variance (Burgess and Webster, 1980a,b; Burrough, 1986). The interpolation weights are derived from statistical analysis of the spatial dependence of the variable.

The spatial variation of sediment deposition in the direction parallel to the river appeared to have a different scale than in the direction perpendicular to the river. This anisotropy of spatial variability is often encountered in fluvial systems (Burrough, 1986). Therefore, separate variograms were made for directions parallel and perpendicular to the main stream. Instead of interpolation values for points or areas of the sample size, we were interested in average estimates over much larger areas. Also, to allow comparison of the interpolation results with other data and model results having a raster format, average estimates for raster cells were required. For this reason, ‘block kriging’ was applied for interpolation of the sediment trap measurements. The interpolation was carried out for raster maps with cells representing 10 m×10 m. At several sections, considerable trends in sediment deposition perpendicular to the main stream were found in the sediment deposition measurements. This resulted in variograms that did not reach a sill. An example for the Klompenwaard is given in Figure 3A. To remove this trend, a technique called ‘universal kriging’ was applied (Webster and Burgess, 1980; Burrough,

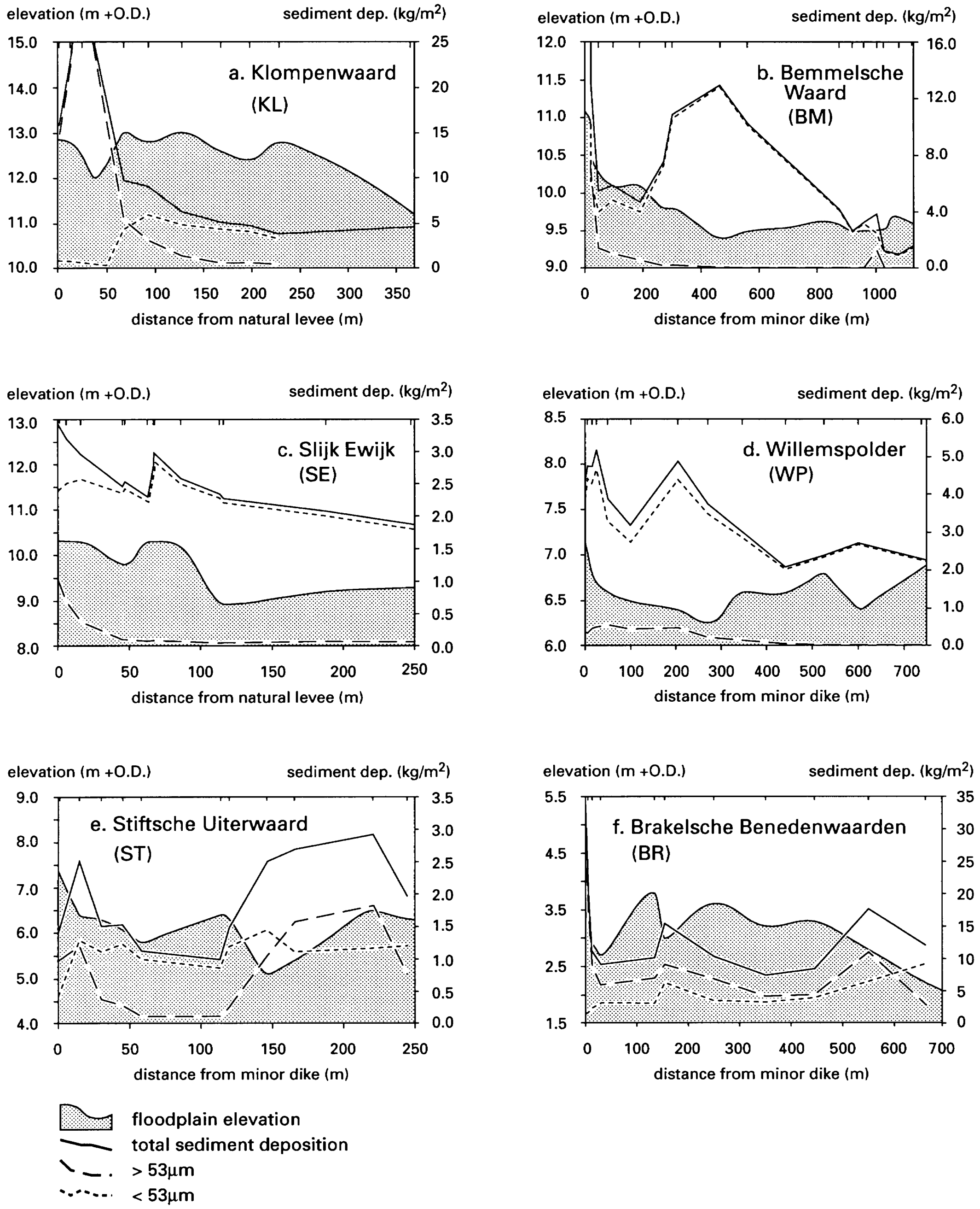

Figure 4. Cross-sections of floodplain elevation and sediment accumulation of the river Waal floodplain sections

1986). Here, the trend was estimated using a linear combination of the log of the distance from the top of the natural levee. The variogram of the residuals after removal of the trend for the Klompenwaard is shown in Figure 3B. The interpolations were carried out using the program GSTAT, developed by Pebesma (1994).

RESULTS

The cross-sections given in Figures 4 and 5 show the relationship between the mass of deposited sediment and distance from the top of the natural levee or the minor river dyke. A distinction is made between the

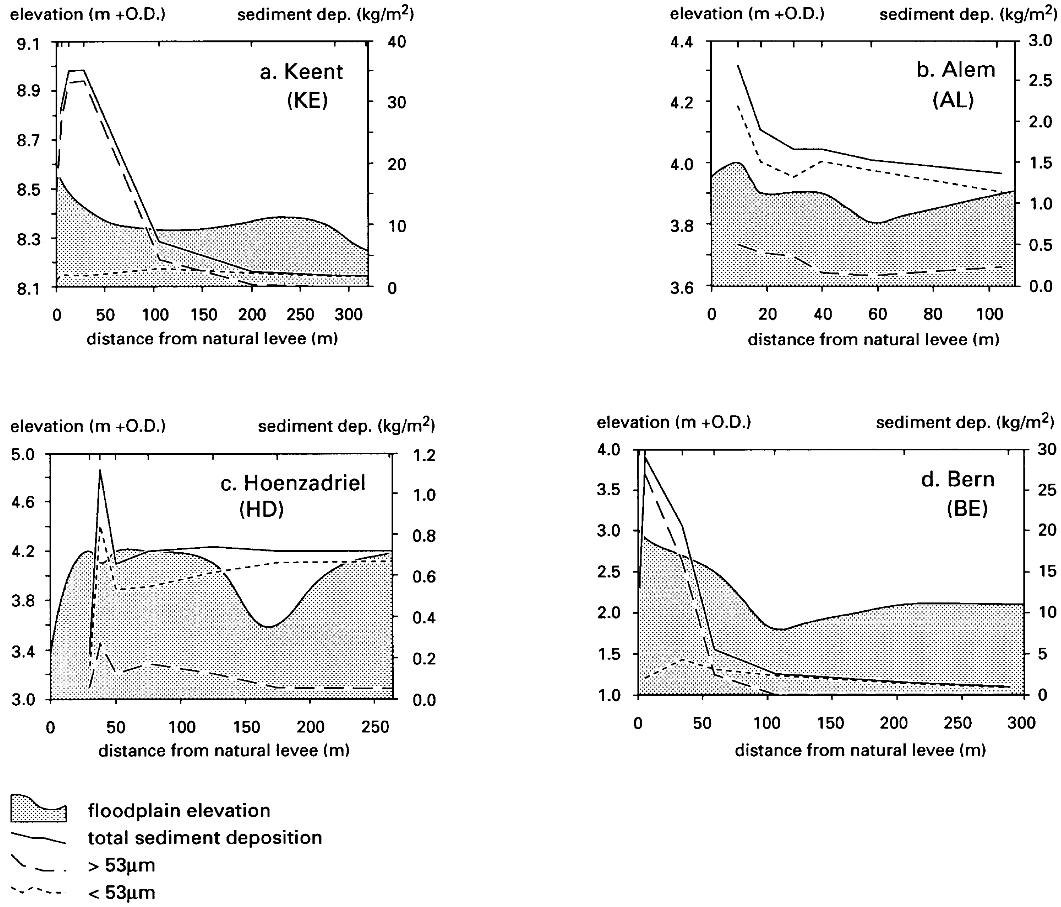

Figure 5. Cross-sections of floodplain elevation and sediment accumulation of the river Meuse floodplain sections

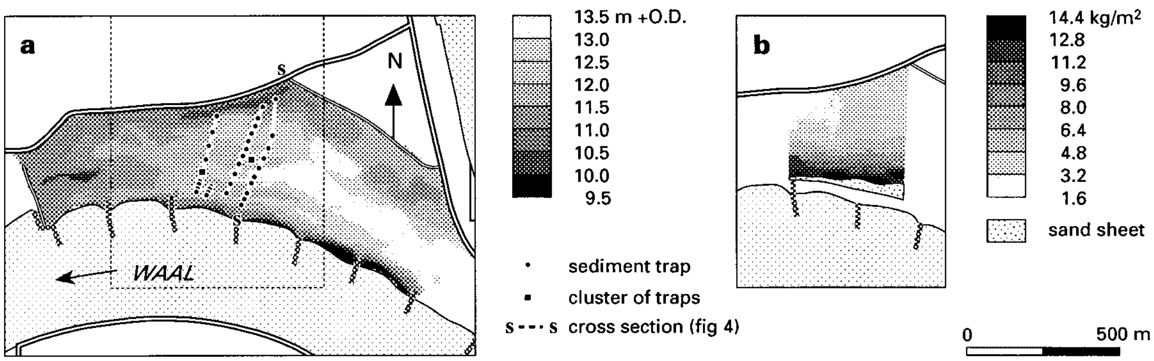

Figure 6. Klompenwaard (KL): (a) floodplain elevation; (b) sediment accumulation

accumulation of sand, and of silt- and clay-sized material. Two-dimensional pictures of the patterns of sediment deposition were obtained from the interpolated raster maps. Typical examples are given in Figures 6 to 9.

During the flood, two types of sediment were deposited on the floodplains: sandy bed load material and silt- and clay-sized wash load material. Deposition of sand was highly variable, and locally formed elongated sand sheets along the natural levees. In most sections, sediment deposition decreased with increasing distance from the river channel. With the exception of the BM and WP sections, depositional patterns are dominated by sand.

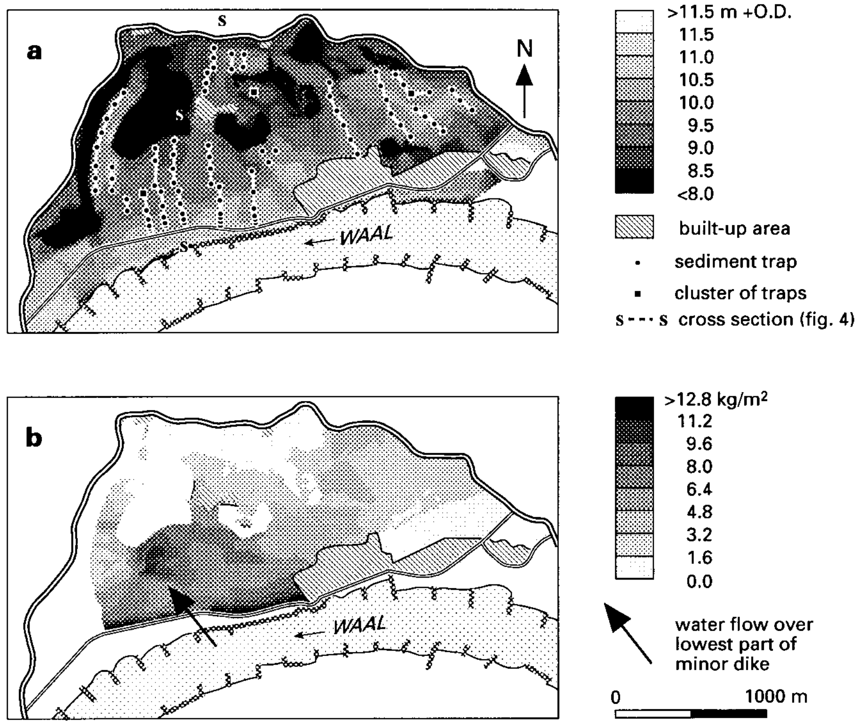

Figure 7. Bemmel (BM): (a) floodplain elevation; (b) sediment accumulation

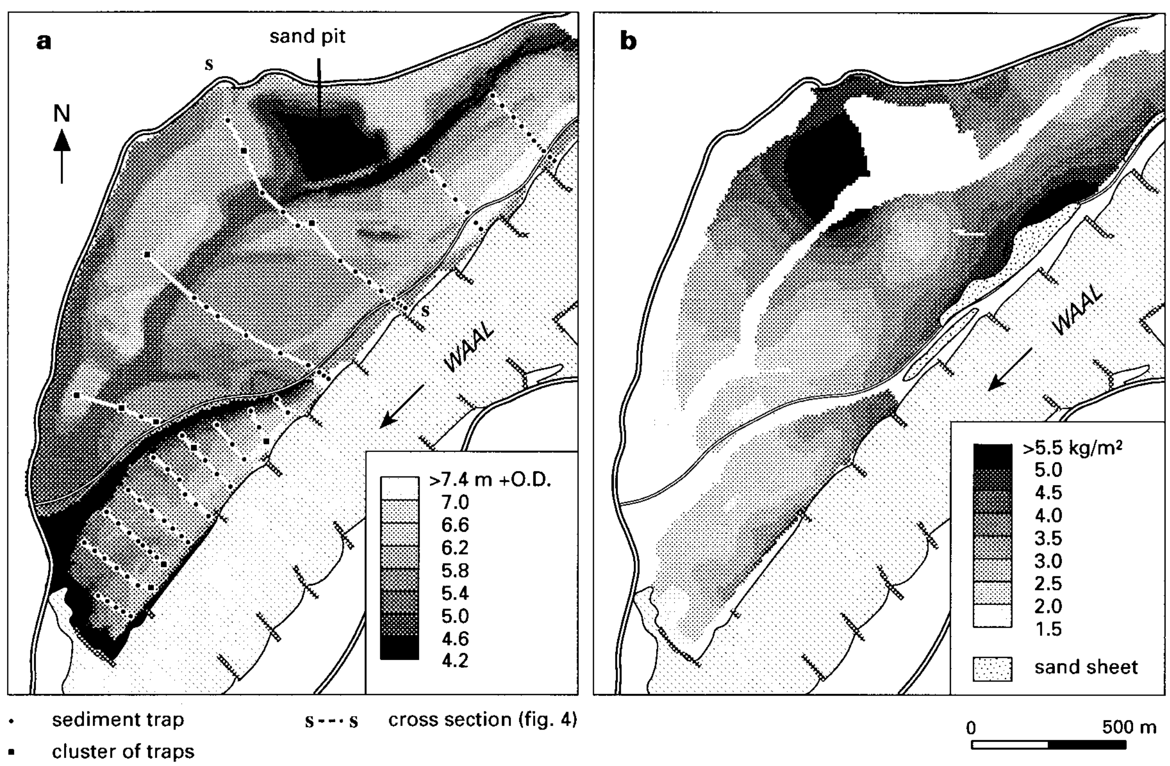

Figure 8. Stiftsche Uiterwaard (ST) and Variksche Plaat (VP): (a) floodplain elevation; (b) sediment accumulation

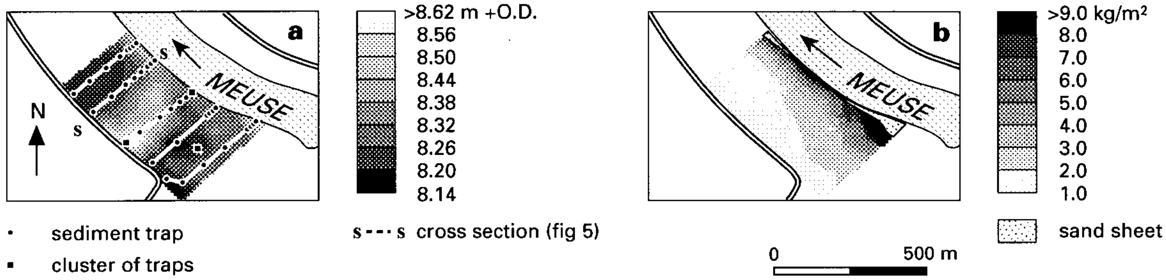

Figure 9. Keent (KE): (a) floodplain elevation; (b) sediment accumulation

Table II. Summary of sediment accumulation at the investigated floodplain sections

	Floodplain sediment accumulation					Sedimentation period (days)	Sedimentation rate ((kg m^{-2}) day^{-1})	
	Average weight (kg m^{-2})		Total weight (10^5 kg)					
	total	<53 µm	total	<53 µm	>53 µm		total	<53 µm
KL	6·61	3·98	8·70	5·23	3·46	23	0·29	0·17
BM	3·86	3·74	88·49	85·84	2·65	15	0·26	0·25
SE	2·24	2·20	2·04	2·01	0·03	20	0·11	0·11
WP	2·58	2·50	25·45	24·68	0·77	12	0·21	0·21
ST*	3·57	1·20	37·60	12·63	24·96	15	0·24	0·08
VP	2·60	2·15	7·28	6·02	1·26	21	0·12	0·10
BR*	6·03	1·50	69·94	17·41	52·53	8	0·75	0·19
KE	4·25	1·74	6·96	2·86	4·11	8	0·53	0·22
AL	1·09	1·00	0·97	0·90	0·08	8	0·14	0·13
BE	4·29	2·00	7·76	3·61	4·14	8	0·54	0·25

* Without sediment from local source

In spite of these common characteristics, however, a considerable variation of patterns was observed, associated with differences in floodplain topography.

For each floodplain section the average deposition of sand, and of silt- and clay-sized material was calculated separately from the interpolated raster maps. The results are summarized in Table II. Sediment accumulation values in kilograms per square metre were converted into millimetres by assuming a sediment density of 1·2 kg dm^{-3}. As the sand sheets strongly influence the average amounts of deposition, comparison of sediment accumulation between different floodplain sections is based on the accumulations of silt- and clay-sized material in the central or the downstream part of the floodplain sections. Average deposition of overbank fines varied between 1·2 and 4·0 kg m^{-2} in the investigated sections along the river Waal, and between 1·0 and 2·0 kg m^{-2} along the river Meuse.

INTERPRETATION

Various factors determined the differences in the amounts and patterns of sediment accumulation that were found after the flood event. These are discussed below.

Floodplain topography

Natural levee. In sections with a low natural levee, such as SE, VP and AL (Figures 4 and 5), sediment deposition decreases exponentially with distance from the natural levee. At a distance of about 50 to 100 m from the levee, the amounts level out to a constant value. When the cross-section data for the amounts of sand are compared with the amounts of silt and clay, it becomes apparent that the exponential decrease depends mainly on the sand deposition. In contrast, the amounts of silt and clay remain almost constant with distance from the main channel when little relief is present (Figure 5). Due to the decrease in sand accumulation with distance from the main channel, the percentages of sand decrease from about 90 per cent at the levee to 5 per cent in the central parts of the Waal floodplain sections, and 15 per cent along the Meuse.

A pronounced natural levee, directly bordering the main channel, can result in a large deposition of sand (KL, KE, BE; Figures 4, 5, 6 and 9). The sand is eroded from the channel bed or the area between the groynes, and transported by traction over the natural levee. Behind the natural levee, current velocities decrease and the sand is deposited in the form of a sand sheet up to 10–25 cm thick. The distal rims of the depositional sand sheets are usually very sharp. The amount of sand deposition on the levee is highly variable in the direction parallel to the river. The large total sediment deposition in the sections KL, KE and BE (Table II) is mainly the result of the sand sheets deposited on the natural levees.

Minor river dykes. Sections BM (Figure 7) and WP are bordered by a 2·5 m high minor dyke. Here, no sand bar or exponential decrease in sediment deposition occurs. A minor dyke reduces the interaction with the flow in the river channel, causing lower current velocities over the floodplain. In addition, only the fine suspended fraction present in the upper part of the water column will enter the floodplain. Maximum sedimentation occurs at the location where the water flows over the minor river dyke. Sedimentation generally decreases with distance from the dyke, but local differences occur.

Though a minor dyke decreases the effective time of sediment transport onto the floodplain, sedimentation rates per day of sediment influx are relatively high (BM, WP; Table II). The minor dyke not only obstructs the incoming, but also the outgoing water flow. Behind the minor dyke, the lower flow velocities and longer residence times lead to a more efficient sedimentation. After recession of the flood, the flood water within the BM and WP sections is ponded behind the minor dyke for 5 to 10 days (Figure 2). Assuming that all the sediment contained in the ponded water settles out during the recession of the flood, this yields an additional sediment accumulation in the order of 100–200 g m^{-2}.

Depressions and residual channels. In the investigated floodplain sections, differences in floodplain elevation are mainly formed by residual channels, and elongated depressions of swales. Deposition in local depressions can be 50 to 100 per cent greater than on higher parts of the floodplain. The effect of a residual channel appeared two-fold. (1) When the residual channel is not closed off from the main channel, such as around the VP section, sediment can be conveyed into the channel. This sediment may accumulate within the channel and the surrounding low-lying areas, especially when discharge is low. (2) During large floods, residual channels are re-activated and current velocities are relatively high. This causes erosion of sediment from the bed, and transport through the channels, resulting in deposition of sand on the channel banks. This occurs, for example, near the residual channel in the ST floodplain section (Figure 8).

Sedimentation processes

Convection and diffusion. The exponential decrease in sediment deposition with distance from the natural levee as found on the floodplains near KL, KE and BE (Figures 6 and 9) closely resembles the ‘ideal’ patterns of sediment transported by turbulent diffusion described by Allen (1985), Pizzuto (1987) and James (1985). The exponential decrease is most pronounced in floodplains without a minor river dyke that are characterized by a uniform relief and little variations in inundation time. Mackey and Bridge (1995) used a similar relation between overbank sedimentation rate and distance from the edge of the channel-belt to model channel-belt aggradation in their three-dimensional model of alluvial stratigraphy. The model simulates the spatial distribution of channel-belt deposits in alluvial strata as a function of channel-belt and floodplain width, and channel-belt and floodplain sedimentation rates. In this model, time-averaged overbank aggradation rate with distance from the channel belt r_{zx} is described by: $r_{\mathrm{zx}} = a_x \exp(-bz_{\mathrm{c}}/z_{\mathrm{m}})$, where a_x is the channel-belt aggradation rate at down-valley distance x, b is the overbank aggradation exponent and $z_{\mathrm{c}}/z_{\mathrm{m}}$ is the normalized distance from the edge of the active channel belt. Mackey and Bridge (1995) state that realistic values of b range between 0·35 and 1·4. This estimate is based on data from Pizzuto (1987). Törnqvist *et al*. (1996) calculated values of b using borehole data from the Rhine–Meuse delta in The Netherlands, and from the Mississippi delta. They concluded that values of b may range from 3 to 7, which is significantly larger that the values assumed by Mackey and Bridge (1995). Although data based on single flood events are less appropriate, the sediment accumulations measured in the present study can be used to estimate values of b. Observed decreases of total sediment deposition yield values of b that are in the order of 5. However, the results of the sections KL, KE and BE (Figures 4 and 5) indicate that the decrease in sediment accumulation is different for different grain size fractions. Accumulation of sand decreases rapidly with distance from the main channel. This yields values for b

between 5 and 10. Accumulation of silt and clay decreases much more gradually. Accordingly, the values for *b* may be less than 1. This difference must be taken into account when estimating or modelling the lateral decrease of overbank aggradation as done in the model of Mackey and Bridge (1995).

Not all floodplain sections are characterized by an exponential decrease in sediment accumulation with distance from the main channel. At those locations the water flow over the floodplain was not parallel to the main channel, but had a component perpendicular to the channel. Here, convection was the dominant transporting mechanism. This is demonstrated by the large amount of sediment deposited in the area behind the overflow section of the minor dyke of the BM area, and by the downstream gradients in the ST and BR sections.

Sediment depletion and local sediment sources. Within some floodplain sections sediment deposition decreases not only with distance from the main channel, but also in a downstream direction. This gradient can be seen on the raster map of ST (Figure 8). In the BR section a downstream gradient in sediment deposition was caused by deposition of sediment eroded from the arable land upstream of the sample area, which acts as a sediment source. No systematic trend in sediment deposition between different floodplain sections in the downstream direction was found. Apparently, variations in floodplain topography have a stronger impact on average sedimentation on a floodplain section than a possible downstream decrease in suspended sediment concentrations in a river reach.

ESTIMATION OF TOTAL ACCUMULATION OF OVERBANK FINES ALONG THE RIVER WAAL DURING THE FLOOD

Using the data from the Waal floodplain sections, an attempt was made to estimate the total amount of suspended sediment deposited on the entire river Waal floodplain during the December 1993 flood. Since the deposition of bed load material is highly variable, even within a single floodplain section, and as it strongly influences the total sediment accumulation, only an estimate of the total accumulation of silt- and clay-sized material was made. For this purpose, it was attempted to establish relationships between morphological characteristics of the investigated floodplain sections and the total amounts of deposited silt and clay, that can be used to predict sediment deposition at unvisited sections. Though sediment deposition was greater in floodplains bordered by a minor dyke, none of the factors listed in Table I appeared useful to estimate sediment deposition in unsampled floodplain sections with greater accuracy than using the overall average. Therefore, total sediment deposition on the entire Waal floodplain was estimated by multiplying the average deposition of overbank fines in the investigated sections (2·56 kg m^{-2}) by the total area of the Waal floodplain (*c.* 95 km^2). This resulted in a total deposition equal to 0·24 Mton. This is about 19 per cent of the total suspended load transported through the river Waal in the same period. It is 7·7 per cent of the average annual suspended sediment load transported by the river Rhine into The Netherlands.

The total amount of bed material deposited on the channel banks during the same flood was estimated by measurements in a separate study by Van Manen *et al*. (1994). They reported that a total volume of bed material of 196 000 m^3 was deposited on the levees. Assuming a bulk density of 1·8 ton m^{-3} (Bierkens, 1994), this is about 0·35 Mton.

CONCLUSIONS

During flooding of the embanked floodplains, two types of sediment are deposited: sandy bedload material and silt- and clay-sized wash load material. The amounts of silt- and clay-sized sediment deposited during the high-magnitude flood of December 1993 ranged between 1·20 and 4·0 kg m^{-2} along the river Waal, and between 1·0 and 2·0 kg m^{-2} in the study areas along the river Meuse. Along both rivers, sedimentation rates ranged between 0·11 and 0·25 kg m^{-2} per day of sediment influx.

The estimated total accumulation of suspended sediment on the entire river Waal floodplain during the December 1993 flood was about 7·7 per cent of the average yearly load of suspended sediment transported by the river Rhine at Lobith. During the flood, the trapping efficiency of the entire Waal floodplain for suspended sediment was about 19 per cent.

In floodplains without a minor dyke, the sand deposition dominates the pattern of total sediment accumulation. The amount of sand deposition decreases exponentially with distance from the levee. This decrease is most pronounced in floodplains without a minor dyke that are characterized by a uniform relief. At distances larger than 50 to 100 m from the river channel, the deposits consist of silty clay. Deposition in local depressions can be 50 to 100 per cent greater than on higher parts of the floodplain.

Behind a minor dyke, sediment deposition shows no clear exponential decrease. Large amounts of sediment are deposited behind the areas where water flows across the minor dyke. Here, the contents of clay and organic matter are relatively high, and the sediment contains little sand. A minor dyke results in a high sedimentation efficiency, with high deposition rates per day of sediment influx. However, the long-term average annual accumulation rate will be low, since these dykes prohibit frequent inundation.

The pattern of exponential decrease of sediment deposition in floodplain sections with a uniform relief agrees well with the diffusion models proposed by Allen (1985), James (1985), and Pizzuto (1987). Many floodplain sections, however, are characterized by an irregular topography or are bordered by a minor river dyke. This results in flow components perpendicular to the main channel. In these floodplain sections convection is the dominant transporting mechanisms of suspended sediment.

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